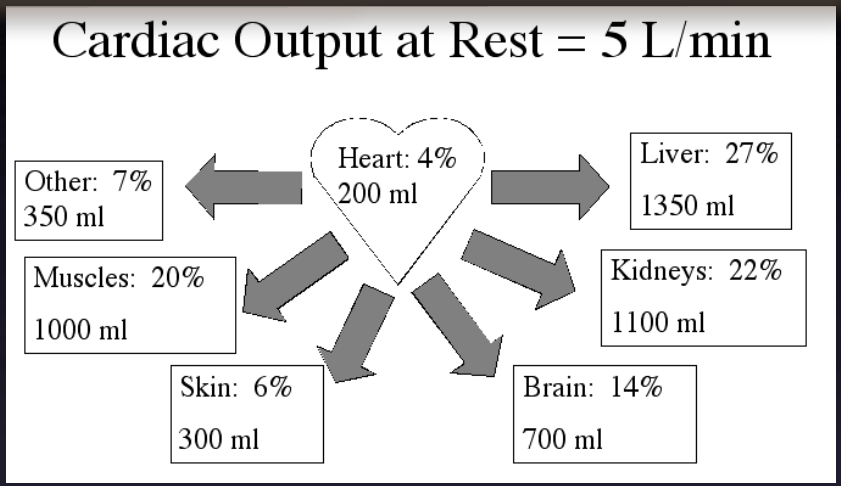
CARDIOVASCULAR SYSTEM

CARDIAC OUTPUT
Regulation of Stroke Volume
(Preload, Contractility & Afterload)



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OBJECTIVES

- **At the end of the lecture you should be able to …..**

1. Define stroke volume, cardiac output, venous return, cardiac index & cardiac reserve
2. Understand the concept of preload and afterload
3. Describe the factors affecting the SV & CO
4. Explains how cardiac contractility & rate affects CO
5. Know the method for measurement of CO (The direct Fick's method)

CARDIAC OUTPUT

Volume of blood ejected by each ventricle in each minute

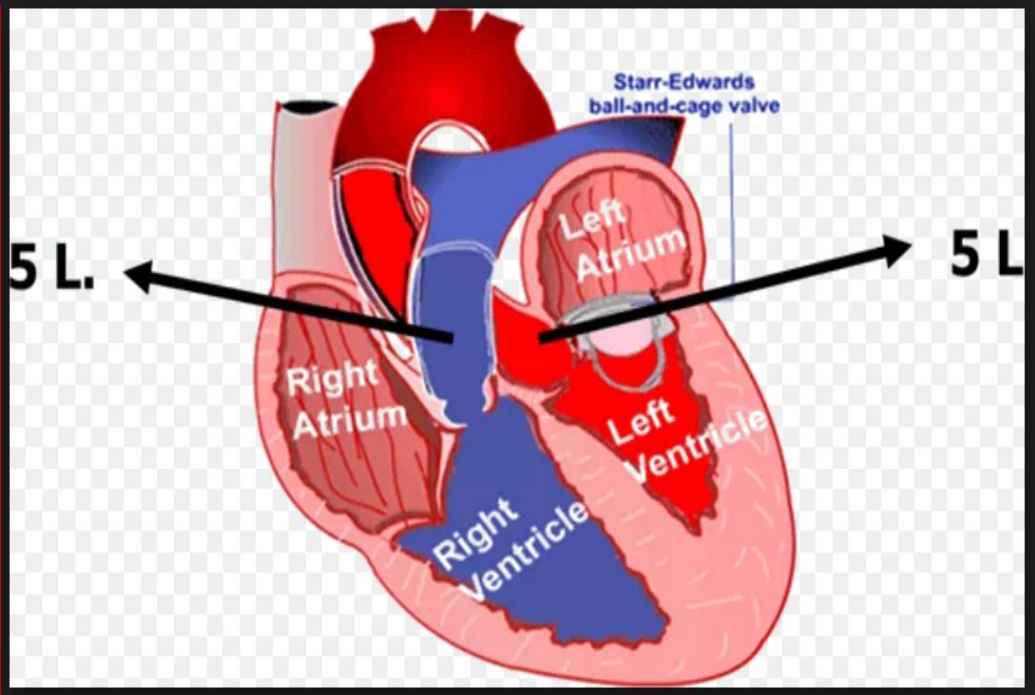
Around 5 liters in an average adult at rest

STROKE VOLUME

Volume of blood ejected by each ventricle per each beat

(SV = EDV - ESV)

Around 70 ml in an average adult at rest



CO = SV X HR

CARDIAC INDEX is Cardiac Output per Square Meter of Body Surface Area

$CI = CO/m^2$

Since : CO vary with Size of individual, Age & Gender (For eg: Women have smaller CO than men)

VENOUS RETURN is the Quantity Of Blood Flowing from the Veins into Right Atrium each Minute

CO = VR

PRELOAD is the amount of blood presented to the Ventricles eg: ↑VR→Preload

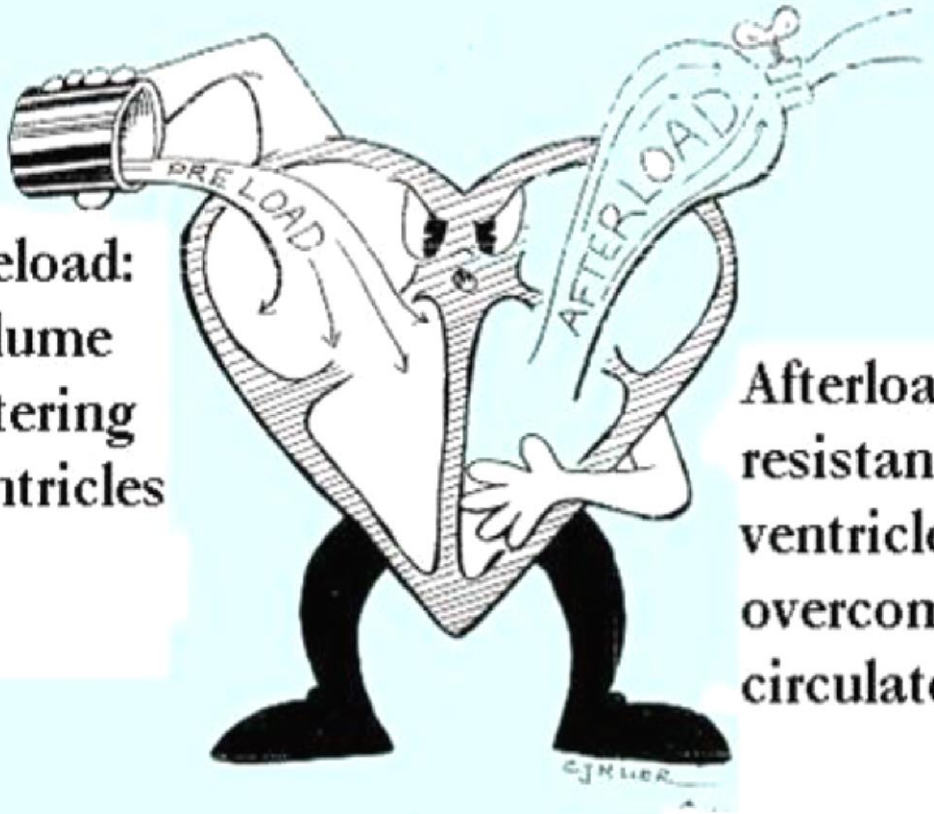
AFTERLOAD is the resistance against Which the ventricles contract eg: Aortic Stenosis → ↑Afterload

CARDIAC RESERVE

During exercise, the CO can increase to 20 - 25 liters/min and to as high as 35 - 40 liters/min in well trained athletes.

The difference between the resting CO and the maximum volume of blood the heart is capable of pumping per minute is known as the cardiac reserve.

Preload and Afterload



Preload: volume entering ventricles

Afterload: resistance left ventricle must overcome to circulate blood

Preload & Afterload

Preload: It is the amount of blood that returns to the heart from veins.

Preload is the load on the muscle in the relaxed state.

Is end-diastolic volume, which is related to right atrial pressure. When venous return increases, end-diastolic volume increases and stretches or lengthens the ventricular muscle fibers

Afterload: It is the resistance against which the ventricles contract.

For the left ventricle is aortic pressure. Increases in aortic pressure cause an increase in afterload on the left ventricle and for the right ventricle is pulmonary artery pressure. Increases in pulmonary artery pressure cause an increase in afterload on the right ventricle.

A. Increased preload: ↑ venous return → **increase in SV** based on the Frank–Starling relationship….reflected in **↑ width** of the PV loop.

B. Increased afterload: due to an increase in aortic pressure → decrease in stroke volume….is reflected in ↓ width & ↑ height of the PV loop.

C. Increased contractility: → **↑ width & ↑ height of the PV loop.**

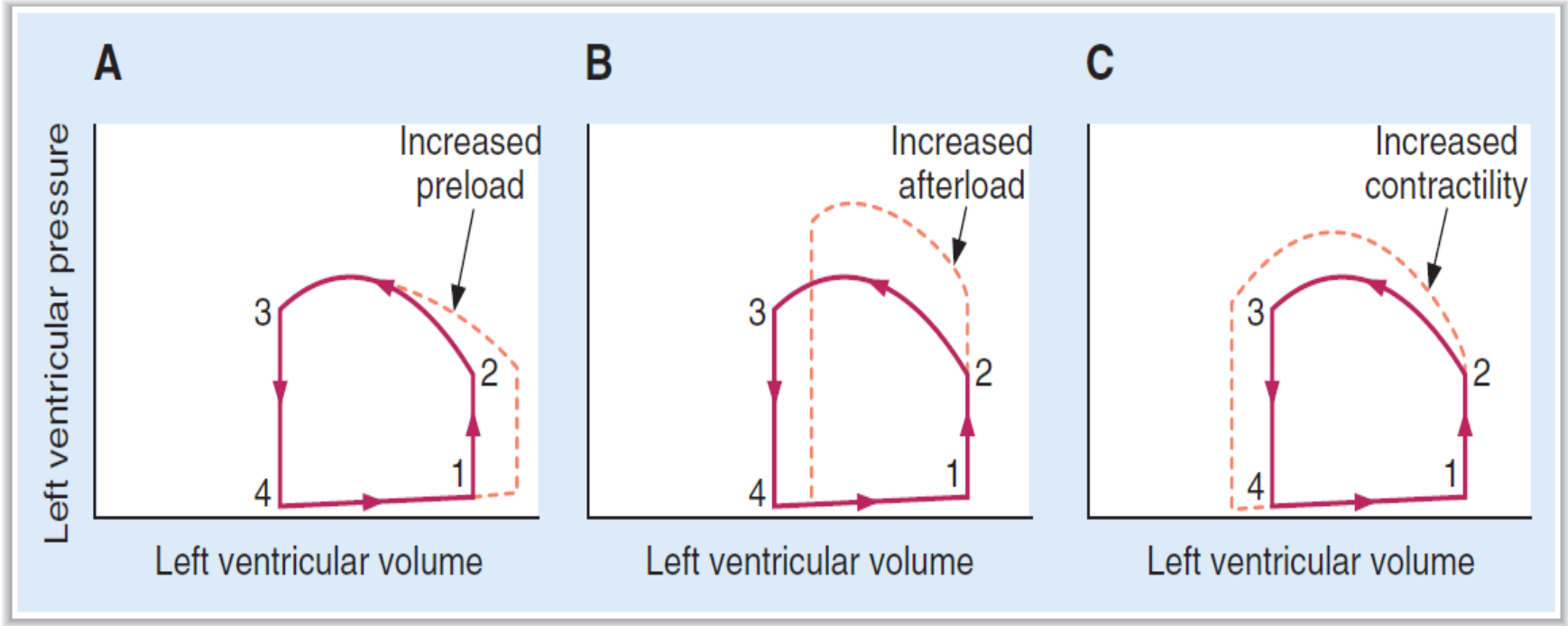
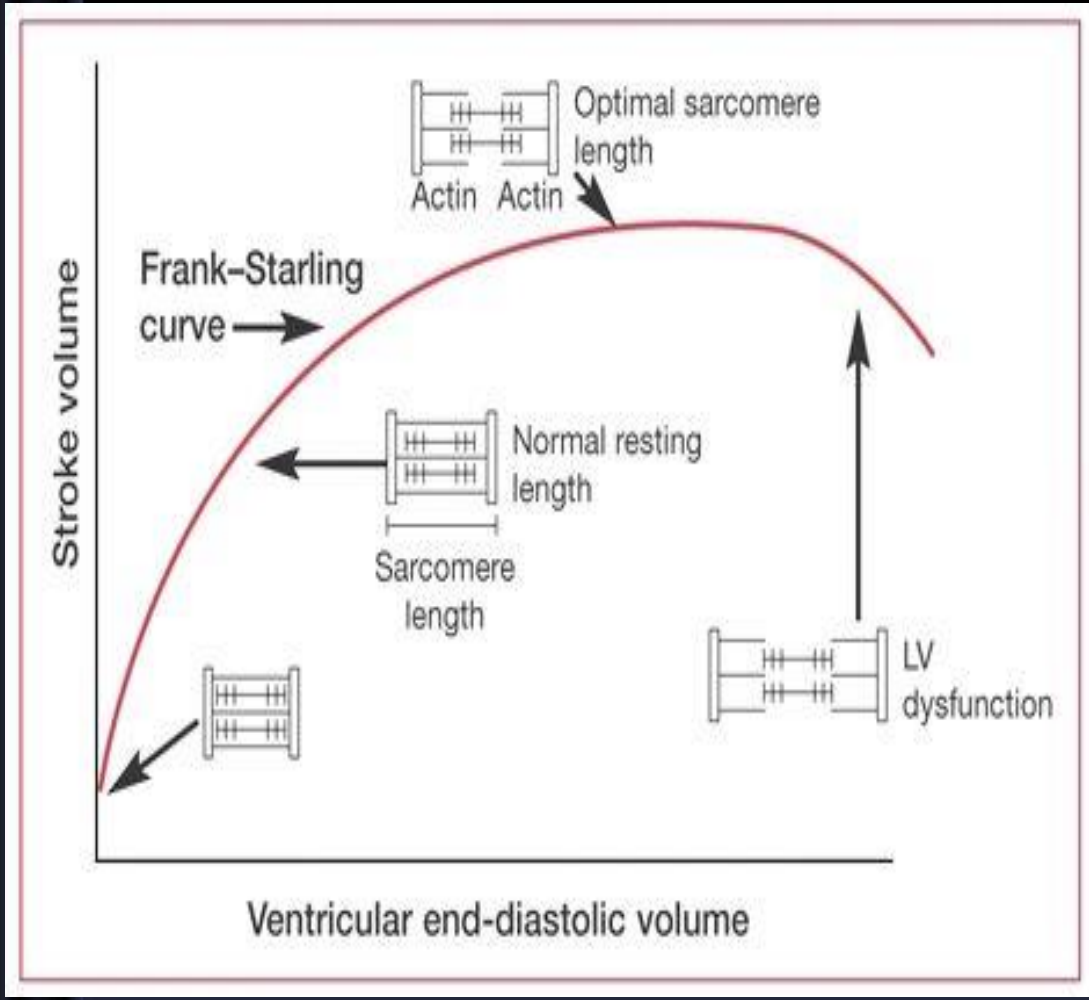


FIGURE 3-10 Effects of changes in (**A**) preload, (**B**) afterload, and (**C**) contractility on the ventricular pressure–volume loop.

Determinants of the CO
Stroke volume (SV)



The **intrinsic relationship** between EDV and SV is known as Starling's Law of the heart. It reflects the ability of the heart to change its force of contraction and therefore stroke volume in response to changes in venous return.

FRANK – STARLING'S LAW

Within physiologic limits, the heart pumps

all the blood that returns to it by the way of the veins.

OR

The greater the stretch of the cardiac muscle the greater would be the force of contraction.

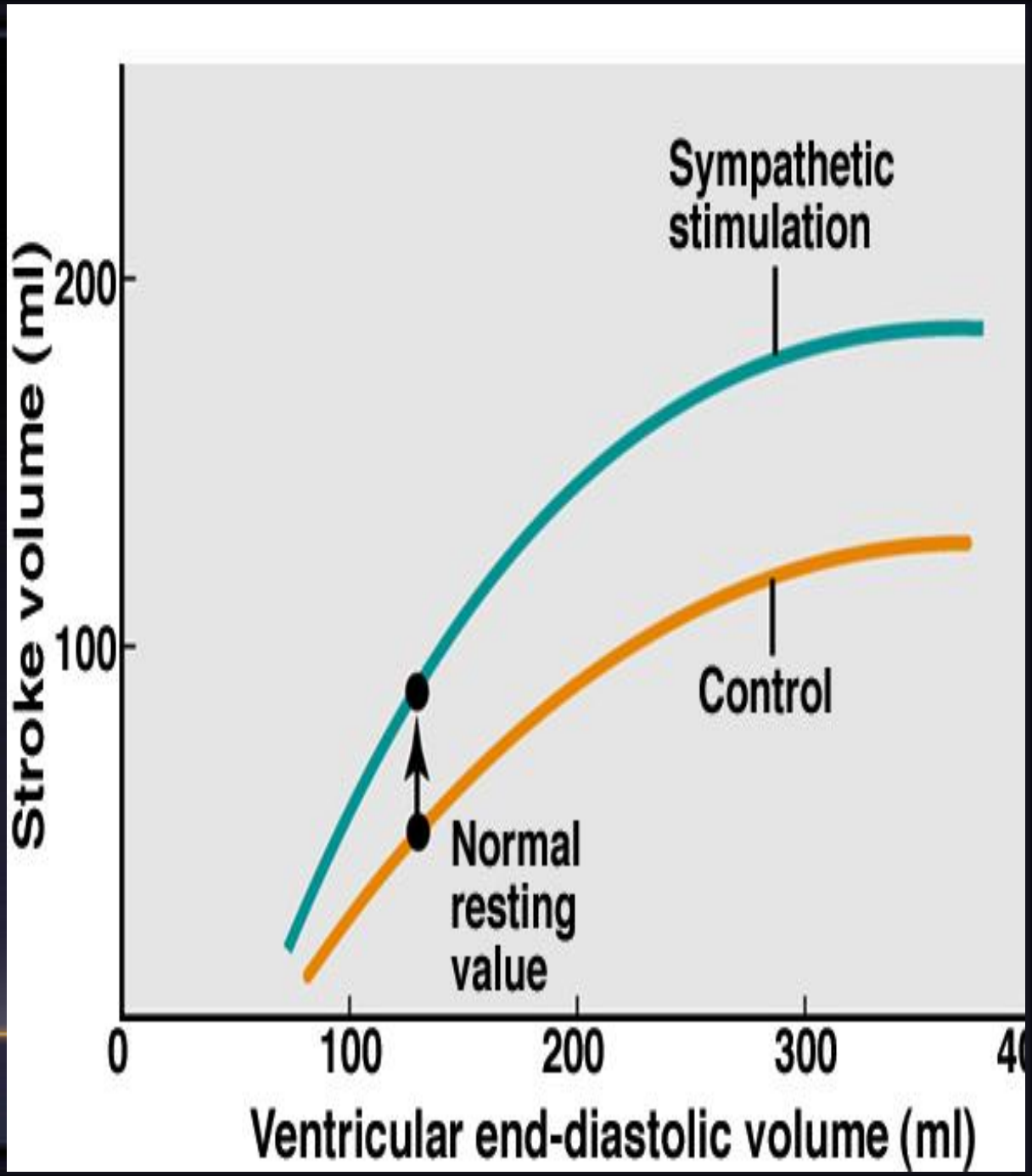
OR

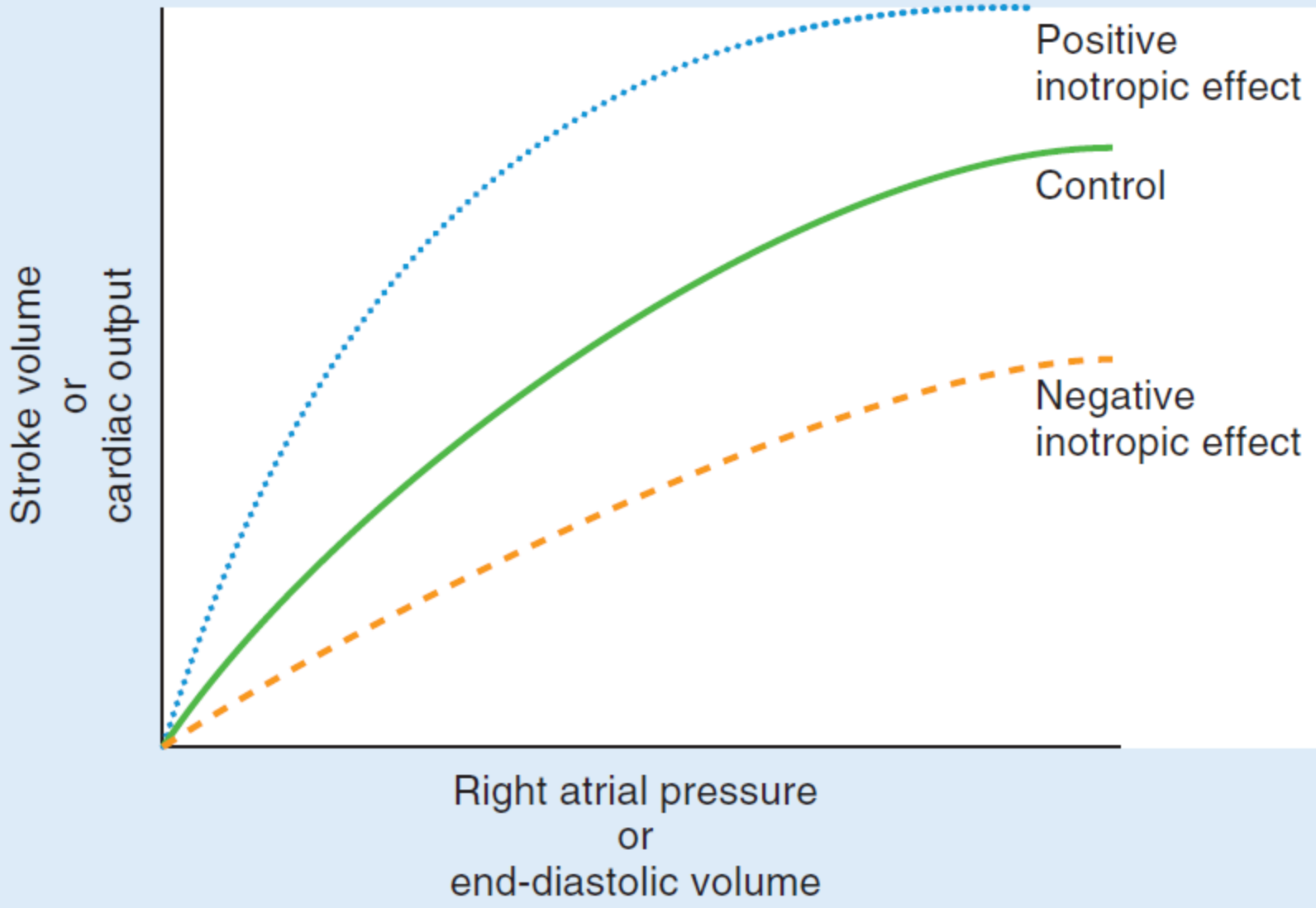
"The energy of contraction is proportional to the initial length of the cardiac muscle fibers" and for the muscle is proportional to the End Diastolic Volume.

Because Actin & Myosin filaments are brought to more optimal degree of sliding therefore increase force of contraction.

- When the mean RAP is about 0 mmHg (note that RAP normally fluctuates with atrial contraction and respiration), the cardiac output in an adult human is about 5 L/min.

- Because of the steepness of the cardiac function curve, very small changes in RAP (just a few mmHg) or EDV, can lead to large changes in cardiac output.




Positive
inotropic effect
Control
Negative
inotropic effect
Stroke volume
or
cardiac output
Right atrial pressure
or
end-diastolic volume

Effect of Afterload on Frank Starling Curve

- An increase in afterload leads to an increase in ESV and a decrease in SV. An increase in afterload shifts Starling's curve down and to the right (from A to B).
- A decrease in afterload shifts Starling's curve up and to the left (A to C).

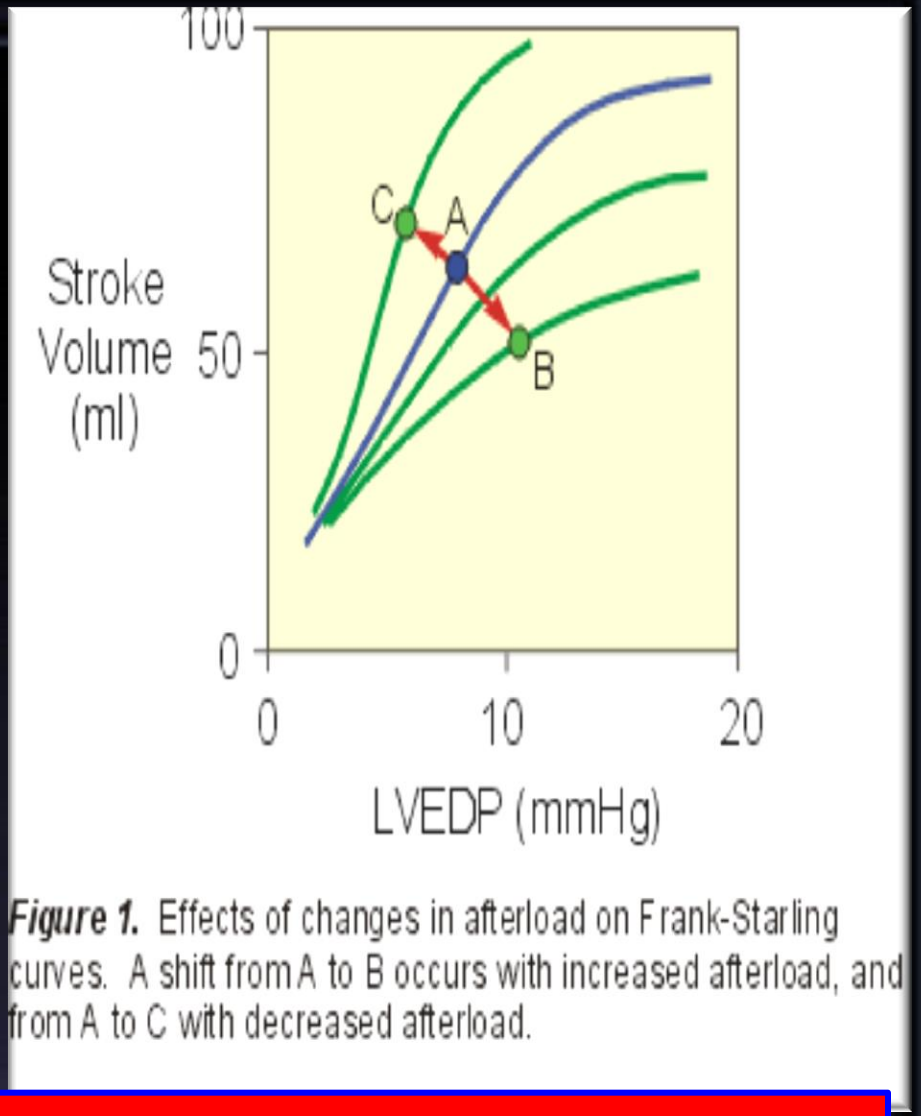


Figure 1. Effects of changes in afterload on Frank-Starling curves. A shift from A to B occurs with increased afterload, and from A to C with decreased afterload.

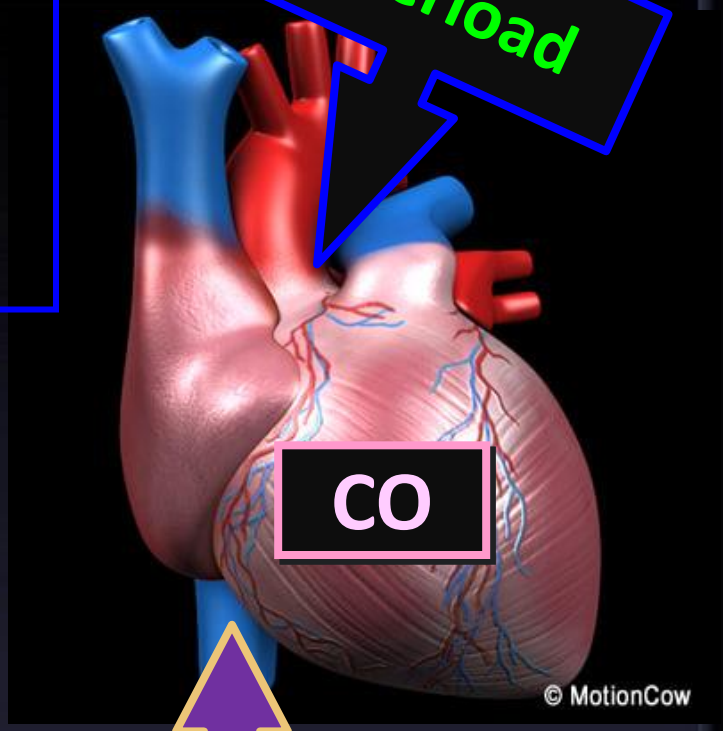
Explanation: an increase in afterload decreases the velocity of fiber shortening. This reduces the rate of volume ejection so that more blood is left within the ventricle at the end of systole → ↑ ESV.

Determinants of the CO

$$CO = SV \times HR$$

OR

$$CO = EDV - ESV \times HR$$



Venous Return

Myocardial Contractility
(Inotropic state)

Heart rate
(Chronotropic state)

Preload ?

Afterload ?

Preload

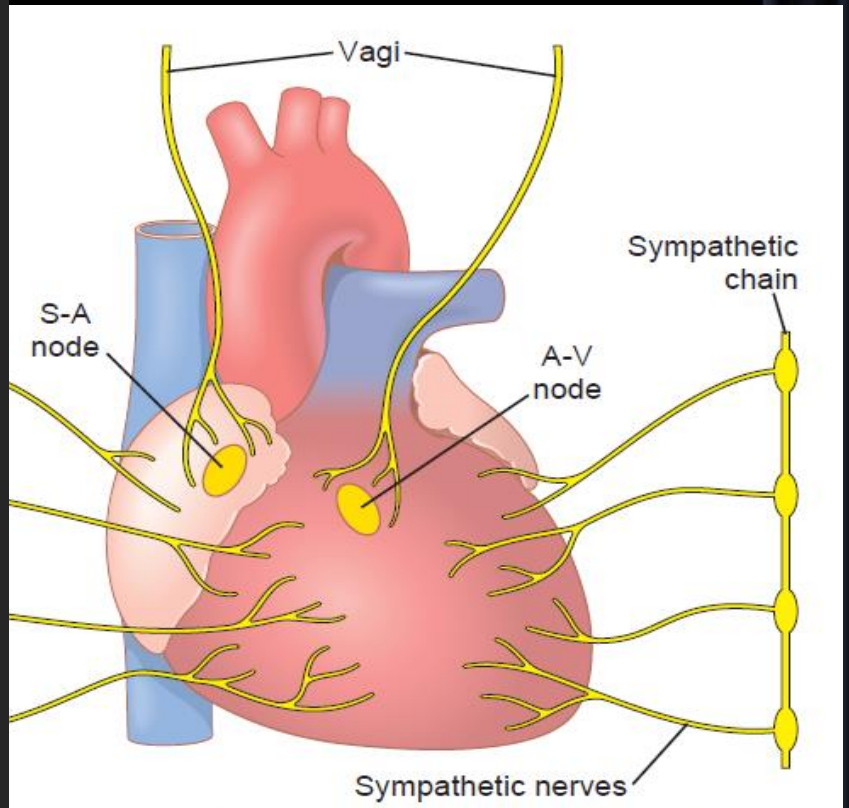
Determinants of the CO
1. Heart rate (HR)

- Since the CO is = SV . HR, as the heart rate increases, CO increases.
- At heart rates up to about 180, ventricular filling is adequate as long as there is enough venous return, and cardiac output per minute is increased by an increase in heart rate.
- However, at very high heart rates, filling may be compromised to such a degree that cardiac output per minute falls.
- The heart rate has an influence on cardiac contractility as well (Frequency-force relationship → due to accumulation of Ca2+ ions within the myocytes).

Regulation of heart rate

Effect of Sympathetic & Parasympathetic Nerves

- Sympathetic nerves innervate the whole heart.
- Sympathetic stimulation increases heart rate (and also the contractility).
- Sympathetic nerves release noradrenaline (adrenaline), which stimulates heart β_1-receptors.
- Parasympathetic nerves innervate the SA and AV nodes, and the atria and Purkinje system.
- Parasympathetic nerves do not innervate most of the ventricular myocardium.
- Parasympathetic stimulation slows the heart but has little inotropic action.
- Parasympathetic nerves release ACh that stimulates muscarinic (M_2) receptors.



9-13. Cardiac *sympathetic* and *parasympathetic* nerves. (The nerves to the heart are parasympathetic nerves.) A-V, atrioventricular; S-A, sinoatrial.

The SA node, atria, and AV node have vagal innervation, but the ventricles do not.

Inotropic Chronotropic & Dromotropic

CONTRACTILITY

Positive inotropic agents produce an increase in contractility.

Negative inotropic agents produce a decrease in contractility

HEART RATE

Positive chronotropic effect

Negative chronotropic effect

CONDUCTION VELOCITY

Positive dromotropic effect

Negative dromotropic effect

Factors affecting myocardial contractility: (Inotropic factors)

1. End-Diastolic Volume [Starling's law of the heart]
2. Cardiac innervation [SNS → ↑, PNS → ↓]
3. Oxygen supply [Hypoxia → ↓ contractility]
4. Calcium ↑ & potassium ions ↓ contractility.
5. Physical factors [Warming → ↑, Cooling → ↓]
6. Mechanical factors [syncytium, cannot be tetanized]
7. Hormonal & chemical factors (drugs).

Positive inotropic: (Adrenaline, noradrenaline, alkalosis, digitalis, Ca^{2+} and caffein)

Negative inotropic: (Acetylcholine, acidosis, ether, chloroform, some bacterial toxins (e.g. diphtheria toxins), K^{+}, …)

Effect of Ions and Temp

- ↑K^+ ions…. in the extracellular fluids causes the heart to become dilated and flaccid and also slows the heart rate… ↑K^+ decreases the resting membrane potential in the cardiac muscle fibers… the intensity of the action potential also decreases, which makes contraction of the heart progressively weaker

- ↑Ca^{++} ions causes spastic contraction. This is caused by a direct effect of calcium ions to initiate the cardiac contractile process. ↓ Ca^{++} causes flaccidity.

- ↑ Temp… causes a greatly increased heart rate, sometimes to as fast as double normal [↑ permeability to ions that self-excitation]. Decreased temperature causes a greatly decreased heart rate, falling to as low as a few beats per minute

FACTORS AFFECTING CONTRACTILITY

- **Positive ionotropic effect. (FORCE OF CONTRACTION)**
  - ✓ Sympathetic stimulation
  - ✓ Adrenaline & Noradrenaline
  - ✓ Calcium ion
  - ✓ Caffeine
  - ✓ Drugs e.g. Digitalis (Digoxin)
- **Negative ionotropic effect:**
  - ✓ Parasympathetic stimulation
  - ✓ Acetyl choline
  - ✓ Potassium ion
  - ✓ Hypoxia (Decrease oxygen)
  - ✓ Acidosis
  - ✓ Bacterial toxin
  - ✓ Drugs e.g.. Calcium channel blockers, β- Blockers

Factors affecting preload (EDV)

EDV is ↑ with:

- Increased total blood volume.
- Increased venous return.
- Increased venous tone.
  - Increased skeletal muscle pump (exercise).
  - Increased negative intrathoracic pressure.
- Stronger atrial contraction.

EDV is ↓ with:

- Standing.
- Decreased venous return.
- Increased intrapericardial pressure.
- Decreased ventricular compliance.

Indices of left ventricular preload:

- Left ventricular end-diastolic volume (LVEDV).
- Left ventricular end-diastolic pressure (LVEDP).

Factors affecting Afterload

Left ventricular afterload represents the force that the muscle must generate to eject the blood into the aorta.

- When the aortic pressure (or Arterial Pressure) is reduced, the velocity of shortening of the LV myocardial fibers increases.
- Hence, with ↓ afterload, the LV can eject blood more rapidly & Easily

  So … {SV ↑ & ESV ↓}
- The opposite is true with increased LV afterload.

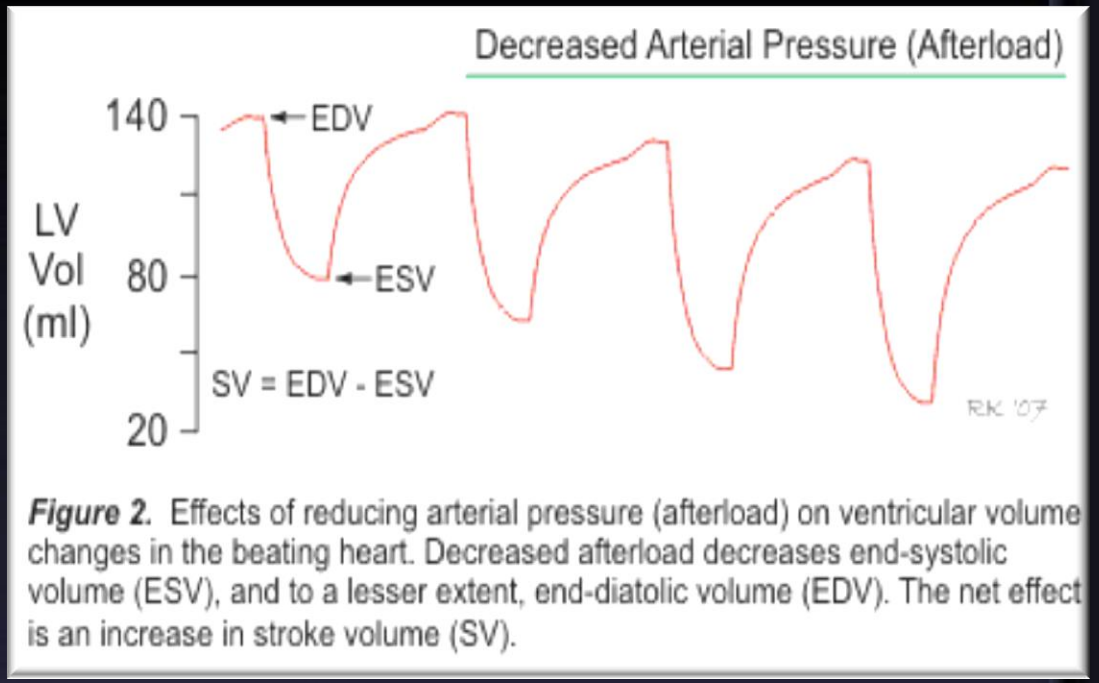


Figure 2. Effects of reducing arterial pressure (afterload) on ventricular volume changes in the beating heart. Decreased afterload decreases end-systolic volume (ESV), and to a lesser extent, end-diatolic volume (EDV). The net effect is an increase in stroke volume (SV).

LV afterload is increased in conditions of aortic stenosis, arterial hypertension & vasoconstriction.

Physiological changes in CO

- During the first 3 hours after meals, the CO is increased by ≈ 30% to enhance blood flow in the intestinal circulation.
- Later months of pregnancy are accompanied by > 30% increase in CO due to increased uterine blood flow.
- At environmental temperature above 30 ˚C, the CO is increased due to increased skin blood flow. Also at low environmental temperature CO is increased due to shivering that increases blood flow to the muscles.
- Increased sympathetic activity during anxiety and excitement enhances the CO up to 50% - 100%.
- Sitting or standing from the lying position deceases the CO by 20% - 30%.
- Exercise:

Effects of exercise on heart rate and SV

Moderate Exercise

- HR increases to 200% of resting (140 bts/min)
- SV increases to 120% (85ml)
- CO increases to 240% (12L)

Severe Exercise

- HR increases to 300% of resting (200 bts/min)
- SV increases to 175% (125ml)
- CO increases to 500% - 700% (25 - 35 L)

- In athletes, maximum CO may be 35L or more - can't increase maximum HR beyond 200 bts - hence - SV increases to 175 ml.

Pathological low or high cardiac output

Causes of low CO:

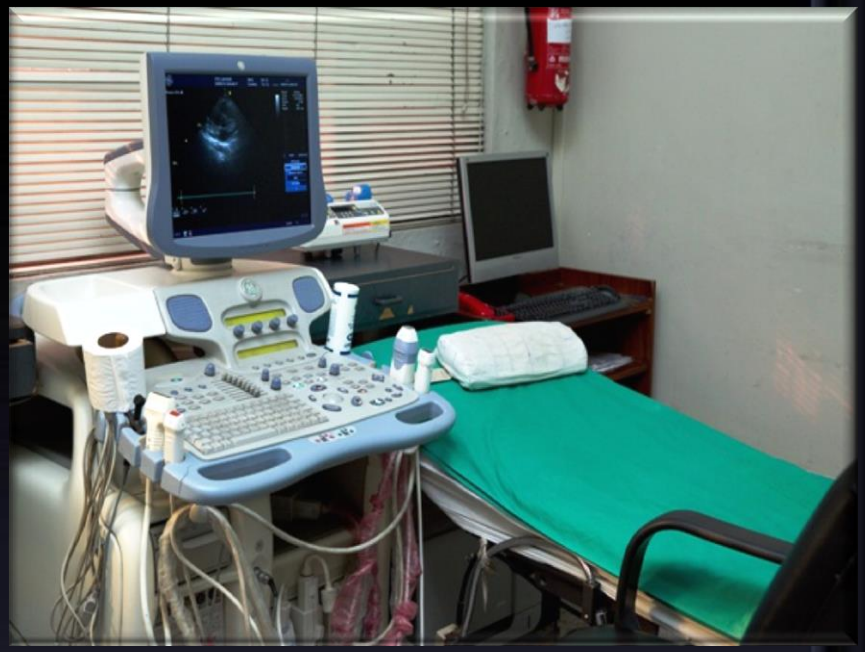
- Low VR (e.g., haemorrhage)
- Reduced contractility (e.g., heart failure)
- Tachyarrhythmias (e.g., atrial fibrillation and ventricular tachycardia)
- Marked bradycardia (e.g., complete heart block)

Causes of high CO:

- Hyperthyroidism: the increase in the CO is due to the high metabolic rate → vasodilatation →↑ CO to 50%+ of control.
- AV fistulas.
- Fever.
- Anaemia.
- Anxiety.

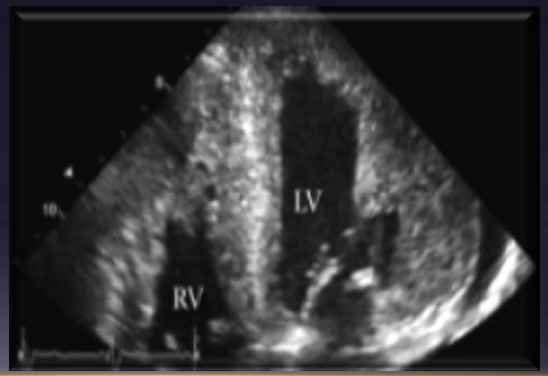
Measurement of cardiac output

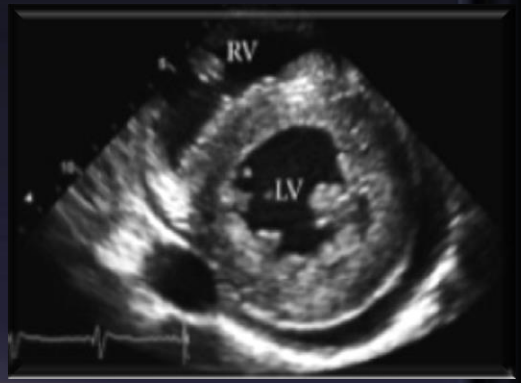
- Ultra-fast computer tomography
- Fick's principle
- 2-Dimensional Echocardiography



2-Dimensional Echocardiography

Records real-time changes in ventricular dimensions during systole and diastole. It thus computes stroke volume, which when multiplied by heart rate, gives the cardiac output.

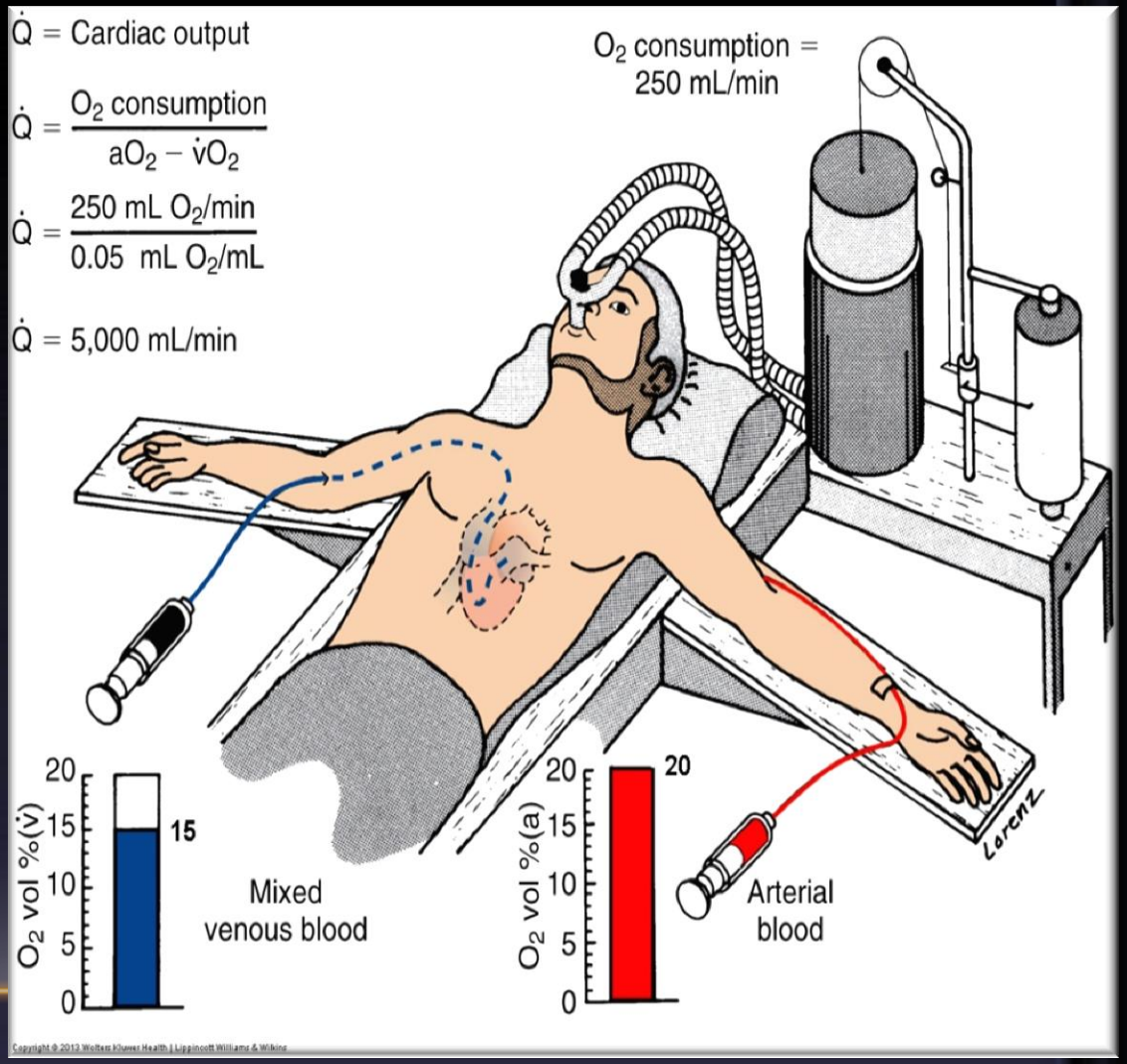




Measurement of cardiac output

Fick's principle

Fick's principle assumes that the amount of oxygen consumed = the amount of oxygen delivered by the arterial blood minus the amount of oxygen e venous blood of the organ.



Measurement of cardiac output

Fick's method

$$CO\ (L) = \frac{\text{Total } O_2 \text{ consumption}}{AO_2 - VO_2}$$

AO_2 = arterial O_2 concentration

VO_2 = mixed venous O_2 concentration